BBC RD 1977/12

1 9 7 4
THE QUEEN'S AWARD
TO INDUSTRY

RESEARCH DEPARTMENT REPORT

L.F. AND M.F. PROPAGATION: a study of sky-wave field-strength variation

P. Knight, M.A., Ph.D., M.I.E.E.

Research Department, Engineering Division
THE BRITISH BROADCASTING CORPORATION March 1977

BBC RD 1977/12
UDC 621.391.812.63

LF AND MF PROPAGATION: A STUDY OF SKY-WAVE FIELD-STRENGTH VARIATION

P. Knight, M.A., Ph.D., M.I.E.E.

Summary

LF and MF sky-waves vary in strength during periods which may be as short as a minute or as long as 11 years; this range includes day-to-day, diurnal, seasonal and solar-cycle variations. A detailed study has been made of all that is known about LF and MF sky-wave field-strength variation and this has been supplemented by further analysis of measured data.

Issued under the authority of

Head of Research Department

**Research Department, Engineering Division,
BRITISH BROADCASTING CORPORATION**

March 1977

(RA-159)

LF AND MF PROPAGATION: A STUDY OF SKY-WAVE FIELD-STRENGTH VARIATION

LF AND MF PROPAGATION: A STUDY OF SKY-WAVE FIELD-STRENGTH VARIATION

P. Knight, M.A., Ph.D., M.I.E.E.

1. Introduction

The strength of LF and MF waves propagated via the ionosphere varies considerably. The greatest change takes place between day and night, because sky waves usually propagate with moderate attenuation during the night but may be almost completely absorbed by the ionosphere during the day. The variation during the night, although smaller, may still be considerable; field strengths vary randomly during periods as short as half an hour and median field strengths measured during short periods on successive nights vary from night to night. In addition, systematic seasonal and solar-cycle variations also occur.

Field-strength prediction methods such as those published by the CCIR[1,2] usually give annual median field strengths, for a short period centred either on midnight or on a specified time after sunset. Corrections for diurnal, seasonal and solar cycle variations are sometimes given and information about the random variations referred to above is contained in a CCIR Report which is concerned with the accuracy with which field strengths may be predicted from a limited number of measurements.[3] In planning a broadcasting service, a detailed knowledge of the magnitude of all kinds of variation, both random and systematic, is required. With this information the probability that sky waves will interfere with ground-wave services can be assessed and the reliability of sky-wave broadcasting services can also be predicted. This report, which includes unpublished work carried out by the BBC, is a survey of present knowledge of LF and MF field-strength variations.

2. Random variation

The ionosphere is a turbulent medium and signals reflected from it are seldom steady. During an hour or less a received signal will usually exhibit several maxima and minima and will vary randomly about a median value. Median field strengths observed at the same time on a series of nights will also be found to vary randomly. These two kinds of variation are considered separately in Sections 2.1. and 2.2. and their combined effect is discussed in Section 2.3. The following notation is used to describe them quantitatively

$F_S(10)$ Ratio of quasi-maximum to median field strength within a short period (dB).

$F_S(90)$ Ratio of median to quasi-minimum field strength within a short period (dB).

$F_D(10)$ Ratio of quasi-maximum of short-period medians to median value of short-period medians (dB), for short periods on a series of nights.

$F_D(90)$ Ratio of median value of short-period medians to quasi-minimum of short-period medians (dB), for short periods on a series of nights.

$F(10)$ Ratio of quasi-maximum to median field strength (dB) for the whole of the time during a series of short periods.

$F(90)$ Ratio of median to quasi-minimum field strength (dB) for the whole of the time during a series of short periods.

In these definitions, a 'short period' means a period of up to one hour's duration. The quasi-maxima and quasi-minima are the 10% and 90% values of the quantities being considered, respectively. Knowledge of the quasi-maximum is of importance when the effects of interfering signals are being assessed but the quasi-minimum need be known only when a sky wave is being used to provide a broadcast service.

2.1. Short-period variation

The continuous random variation of sky-wave signals is often referred to as fading. Two parameters which describe fading signals are the amplitude distribution and the fading frequency. Both are discussed in this section.

2.1.1. Amplitude distribution

Amplitude distributions of fading signals have been studied extensively and their mathematical properties are described elsewhere.[4] Nearly all the distributions which have been observed at LF and MF conform either to one of three basic types or to a distribution which lies between two of them.[5,6,7,8] The three basic distributions and two intermediate distributions are represented diagramatically in Fig. 1.

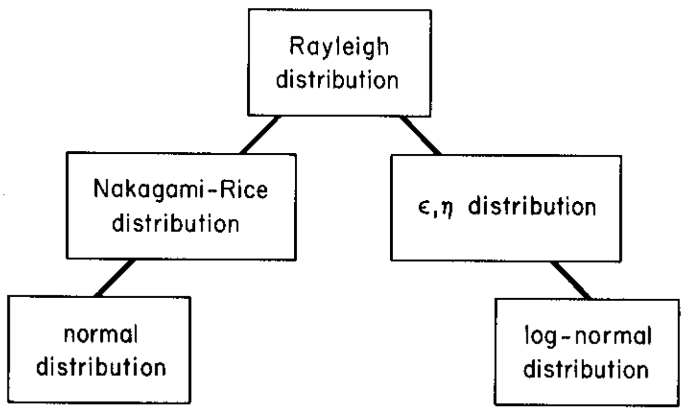

Fig. 1 - Amplitude distributions of fading signals

The Rayleigh distribution arises if the resultant signal consists of a large number of randomly-phased signals of comparable amplitude. If one component predominates, however, the amplitude distribution approaches the normal or gaussian distribution via the Nakagami-Rice distribution.[9,10] In the log-normal distribution the field strength expressed in decibels is normally-distributed. The distribution which tends either to the Rayleigh or to the log-normal distribution in limiting cases, has been called the ϵ,η distribution.[7,8]

Bi-modal distributions[11,12] have also been observed; they have amplitude probability curves with two distinct maxima. As the name suggests, they probably arise when the propagation mode changes during the period of observation.

Some of the distributions which have been observed are compared in Fig. 2. The log-normal distribution (not shown) would be a straight line with a gradient proportional to its standard deviation. Although these cumulative distribution curves differ considerably when the field strength is less than the median value, Fig. 2 shows that all the distributions are approximately log-normal when the median is exceeded.

Detailed studies of the difference (in decibels) between quasi-maximum and median field strengths, measured during periods of one hour or less, have been made by the ORTF for the EBU.[13] A similar study has been made by NHK[14] and further work has been carried out by other broadcasting organisations, including the BBC.[7,8,15] The ORTF studied the ratio of field strengths exceeded for 10% and 50% of the time while NHK studied the difference in decibels between field strengths exceeded for 5% and 50% of the time. To facilitate comparison, the NHK measurements have been converted to differences in dBs between field strengths exceeded for 10% and 50% of the time by assuming the distributions to be log-normal above their median values.

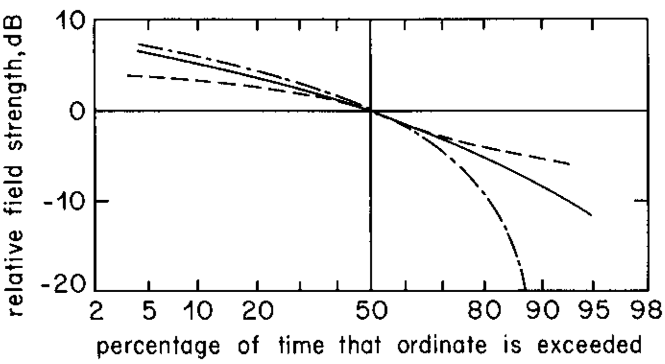

Fig. 2 - Comparison of cumulative frequency distributions

——— Rayleigh distribution
—·— Gaussian distribution
---- Measured bi-modal distribution (from Reference 12)

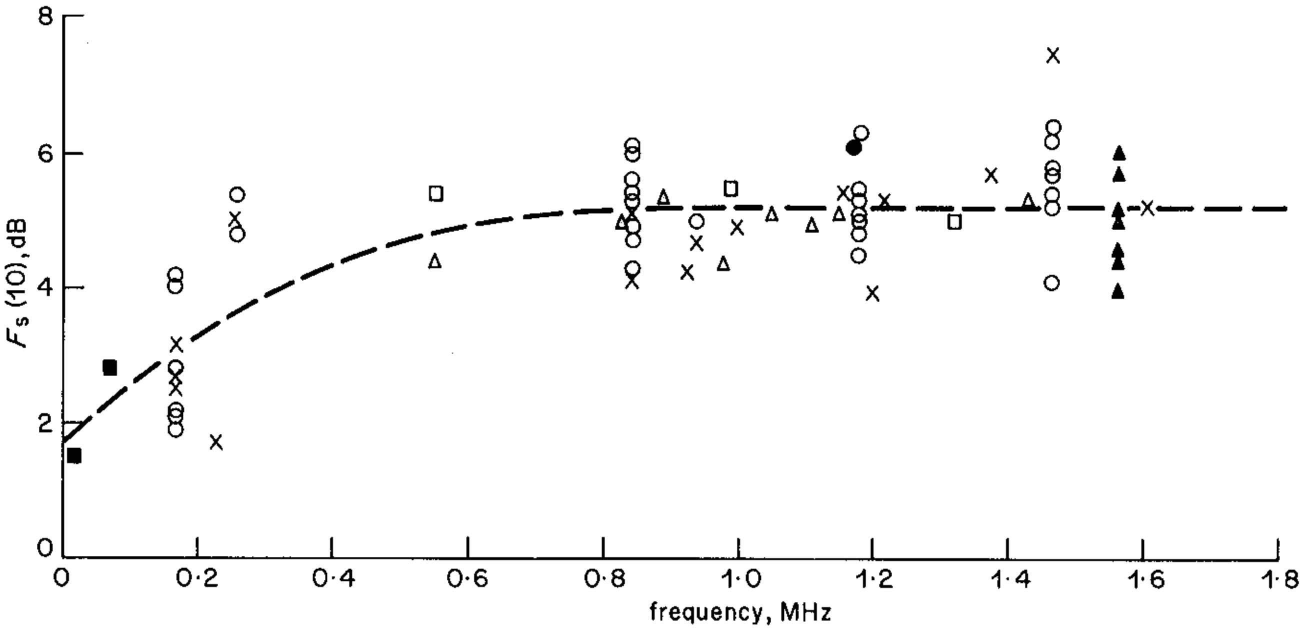

Fig. 3 - Difference between quasi-maximum and median field strengths observed during short periods

O ORTF analysis of EBU measurements (Reference 13)
X BBC analysis of EBU measurements and other measurements made by the BBC
Δ NHK measurements (Reference 14)
● OIRT measurements (Reference 8)
□ Australian measurements (Reference 15)
▲ Unpublished EBU measurements
■ Measurements described in Reference 16 and 17

Both the ORTF and NHK found that differences between quasi-maximum and median field strengths vary from night-to-night. A detailed study by the BBC of measurements made on three typical paths showed that the difference between 10% and median values, $F_S(10)$, decreases when the median field strength increases, probably because one of the components of the received signal is stronger than the others and therefore predominates. Attenuation is confined here to median values of $F_S(10)$.

Fig. 5 of Reference 13 shows that the median value of $F_S(10)$ is almost independent of path length (except at LF) but tends to increase with increasing frequency. This tendency is illustrated in Fig. 3, where all known median values of $F_S(10)$ measured at night have been plotted against frequency. In addition to LF and MF measurements, Fig. 3 includes a single value measured at 16 kHz on a 100 km path[16] and the mean of two values measured at 70 kHz on a 1637 km path in Canada.[17]

At the higher frequencies in the MF band the average value of $F_S(10)$, shown by a broken line, is close to the value of 5·2 dB which applies to the Rayleigh distribution; this is consistent with the fact that the Rayleigh distribution is usually observed at HF.[18,19] The tendency for $F_S(10)$ to decrease as the frequency decreases indicates the presence of a dominant wave component and suggests that quasi-specular reflection occurs at the lower frequencies. It is uncertain whether the larger values of $F_S(10)$ measured at LF on the shorter paths are the result of interference between the sky wave and the ground wave or are the result of a transition from quasi-specular reflection at very oblique incidence to non-specular reflection at steep incidence.

Fig. 3 applies to propagation at night. LF and MF waves sometimes propagate during the day, and BBC measurements have shown that smaller values of $F_S(10)$ are observed at LF, suggesting a greater tendency towards specular reflection in daytime. On the Warsaw-Kingswood path (227 kHz, 1370 km), for example, the median values of $F_S(10)$ were found to be 1·7 dB and 3·0 dB during the day and night respectively.

Less information is available about the difference between the median field strength and the quasi-minimum but measurements have shown that $F_S(90)$ slightly exceeds the Rayleigh value of 8·2 dB at MF.[8,12] At lower frequencies $F_S(10)$ and $F_S(90)$ are approximately equal, as would be expected when one wave component predominates.

2.1.2. Fading frequency

Some of the parameters which are used to define fading frequency are described in Section 4.2. of Reference 4. The simplest and least ambiguous parameter is the number of times the signal exceeds the median value during a stated time, denoted here by N. On long-distance paths in Europe, a typical value for N at 1 MHz would be 10 per hour.

Measurements show that N varies considerably with frequency and path length. In a study[6] of measurements of an alternative fading parameter it has been suggested that fading frequency might be proportional to $f\cos i$, where f is the frequency and i is the angle of incidence at the ionosphere. Fig. 4 shows median values of N for MF, measured by NHK in Japan,[14] plotted against $f\cos i$, together with Australian MF measurements[20] and a few values of N derived from LF and MF measurements made near London by the BBC. All three sets of measurements obey the linear relationship but the gradients of the lines vary considerably. Although the values of N measured by NHK are more than twice the Australian and European values, they are comparable with Indian measurements of the number of fades per hour.[12] NHK also found that fading frequencies in Japan are greatest in the summer, unlike Europe, where fading has been found to be approximately 1·5 times faster at midwinter than at midsummer.[6]

On some paths appreciable diurnal variations in fading frequency are observed. For example, at the higher frequencies in the MF band, slow fading due to E-layer propagation may be superseded by the more rapid fading characteristic of F-layer propagation, with even more rapid fading when the two propagation modes are received simultaneously. A sudden reduction of fading frequency often occurs at sunrise, especially if F layer propagation is replaced by E-layer reflection during the short period (typically half an hour) before the signal fades out.

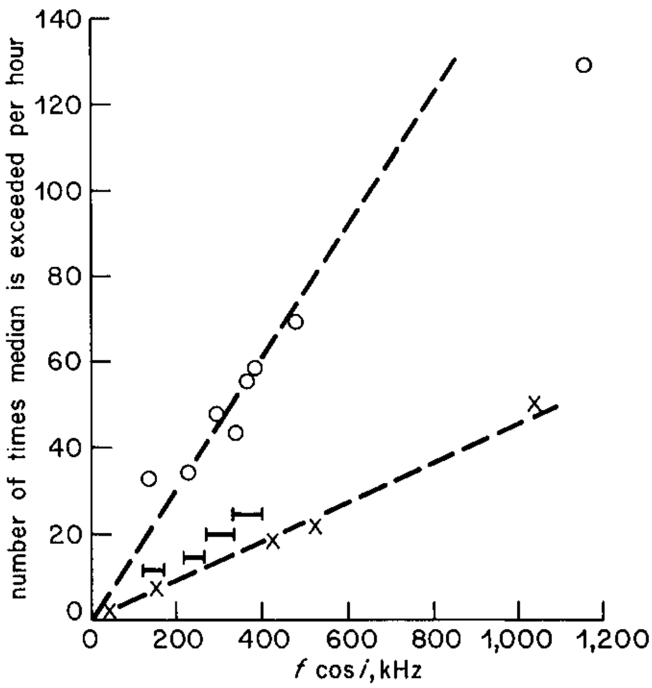

Fig. 4 - Fading frequency

O NHK measurements (Reference 14)

X BBC measurements

⊢⊣ Australian measurements (Reference 20)

2.2. Day-to-day variation

Median field strengths for half-hour or one-hour periods, measured at a given time after sunset on a series of nights, vary randomly with a log-normal distribution. A good indication of the extent of this day-to-day variation is given by the quantities $F_D(10)$ and $F_D(90)$ defined in Section 2.

In determining these quantities from a series of measurements, care must be taken to eliminate diurnal, seasonal and solar-cycle effects. Diurnal variation is eliminated by ensuring that only those measurements which were made at the same time relative to sunset or sunrise are analysed, while seasonal variation is minimised if the analysis is restricted to measurement periods of less than three months. Solar-cycle variation need only be considered if measurements made over a series of years during a particular month or season are being analysed together.

Numerous measurements of $F_D(10)$ and $F_D(90)$ which satisfy these criteria are to be found in the literature. Fig. 17 of Reference 13, Fig. 1 or Reference 21 and Fig. 13 of Reference 22 give values for MF night-time propagation over medium and long distances while values for short-distance day and night LF propagation are given by Figs. 4, 6, 7, 8 and 9 of Reference 23. Values for long-distance MF paths may also be derived from some of the measurements[24] which formed the basis of the Cairo propagation curves. Values for short and medium-distance MF propagation in Africa were derived from Figs. 4, 5 and 6 of Reference 25 and calculated from standard deviations and quartile values tabulated in Reference 26 by multiplying by the appropriate factors. Indian measurements of $F_D(10)$ and $F_D(90)$ for night-time propagation at 280 kHz are shown in Fig. 2(b) of Reference 27. Further values were obtained from a BBC analysis of EBU measurements and from measurements made by the BBC. In all, more than 100 values of both $F_D(10)$ and $F_D(90)$, for frequencies between 164 and 1602 kHz and path lengths up to 8400 km, were available for further study.

All the values measured at night were grouped together because they showed no obvious dependence on frequency or path length. $F_D(10)$ had a median value of 5·5 dB, 90% of the values being within the range 3·5 dB to 8·8 dB. $F_D(90)$ had a similar distribution. with a median value of 6·0 dB. Slightly greater values have been derived from measurements made in the USSR,[28] but it is not clear whether seasonal effects were excluded before the Russian data were analysed. BBC measurements of LF daytime propagation gave values of 4·4 dB and 7·8 dB for $F_D(10)$ and $F_D(90)$ respectively.

2.3. The combined effect of short-period and day-to-day variation

Both the short-period and day-to-day variations contribute to the overall variation of the received signal. In planning broadcasting services a knowledge of their combined effect is required.

If both of these variations are log-normal and independent of each other, the overall variation will also be log-normal and will have a variance equal to the sum of the individual variances. It then follows that $F(10)$, the amount by which the field strength exceeds the overall median for the whole of the time, is given by

$$F(10)^2 = F_S(10)^2 + F_D(10)^2 \quad (1)$$

A similar expression applies for $F(90)$

$$F(90)^2 = F_S(90)^2 + F_D(90)^2 \quad (2)$$

Equations (1) and (2) may be used even if the distributions are not log-normal, provided the sections of the distributions between the 10% and 50% points, and between the 50% and 90% points are approximately log normal. Fig. 2 shows that the use of the log-normal approximation is reasonable when the field strength exceeds the median but has less justification below the median. Thus Equation (1) is valid but Equation (2) should be used with caution.

The other assumption which was made is that the two variations are mutually independent. This however is not true because measurements show that the short-period variations are smaller when the median field-strength for the short period is above average, as might be expected. However a numerical calculation of the overall distribution curve which arises when the interdependence of the two distributions, measured on a typical path, is taken into account has shown that very little error arises if Equation (1) is used.

Fig. 3 suggests that it is reasonable to assume that $F_S(10)$ has values of 3·2 dB and 5·2 dB at night at LF and MF respectively. If $F_D(10)$ is assumed to be 5·5 dB at night for all frequencies it follows that $F(10)$ has values of 6·4 dB and 7·5 dB at LF and MF respectively. These values are slightly less than those quoted in Section 4 of the Annex of CCIR Report 575 (Reference 2) because the figures in Report 575 include the effect of seasonal variation, discussed in Section 4. For LF daytime propagation, the values of $F_S(10)$ and $F_D(10)$ quoted in the previous sections lead to a value of 4·7 dB for $F(10)$.

3. Diurnal variation

By far the largest variation of LF and MF sky-wave field strength is that which occurs during 24 hours. The diurnal variation is difficult to measure during the day, however, because the daytime sky-wave is often obscured by the ground wave. Fig. 5 shows the results of two measurements in which this difficulty has been overcome.

Fig. 5(a) shows ionospheric reflection coefficients for LF daytime propagation deduced from the amplitudes of ground wave/sky-wave interference patterns;[29] the sky-wave field strength is, of course, proportional to the reflection coefficient. The measurements shown in Fig. 5(a) were made at sunspot minimum on a 1000 km European path. Reference 29 does not give night-time

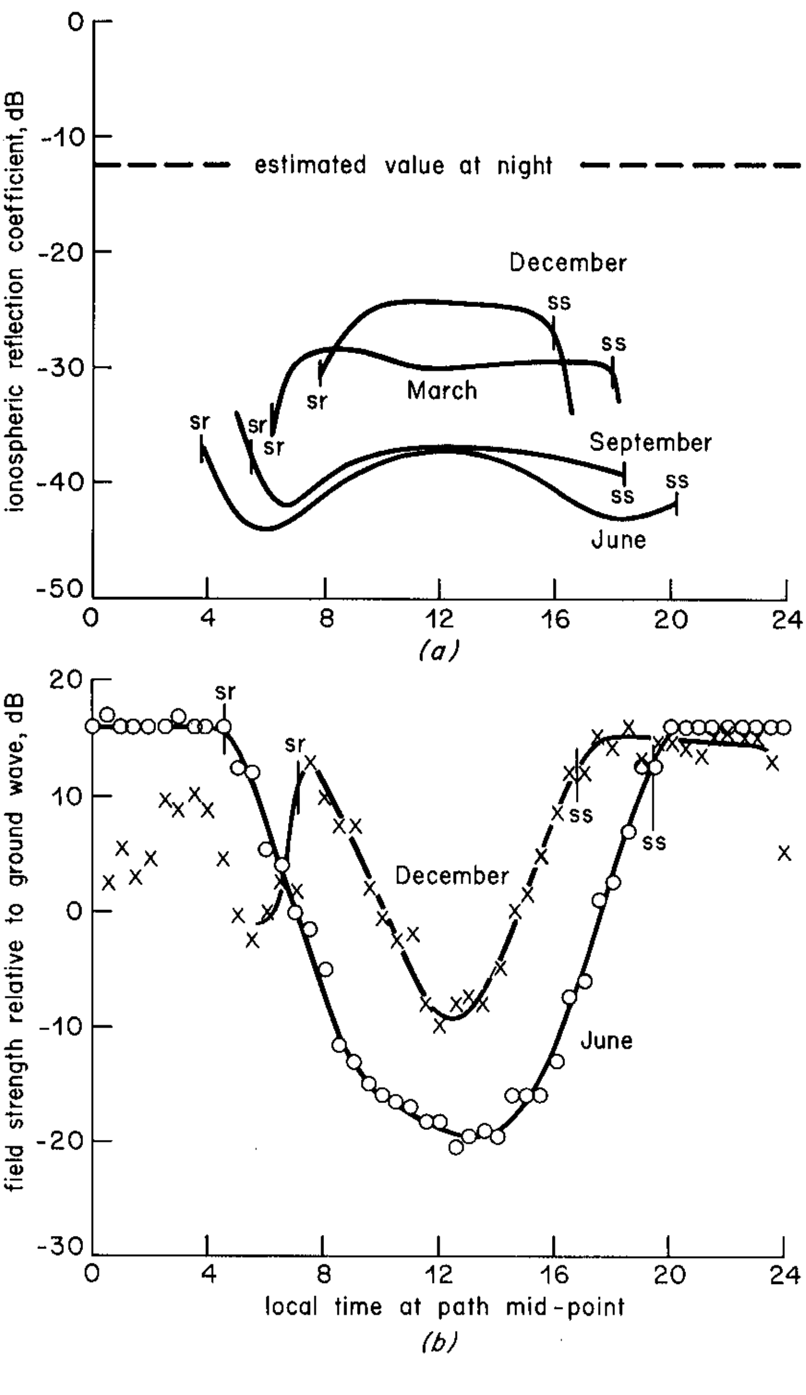

Fig. 5 - Diurnal variation

(a) Measured at 164 kHz on the Allouis–Kolberg path (1000 km) in 1964. (From Reference 29)

(b) Measured at 1850 kHz on a 361 km path in Japan in 1964. (From Reference 33)

SR Ground sunrise at path mid-point
SS Ground sunset at path mid-point

The points in Fig. 5(b) indicate monthly median values for half-hour periods

reflection coefficients but a value estimated from a CCIR Report[30] which is mainly concerned with propagation at lower frequencies has been added to Fig. 5(a).

The most noticeable feature of LF daytime propagation is the seasonal variation, discussed in more detail in Section 4. Another feature is the mid-day maximum; this has also been observed in India, where a close correlation between field strength and solar zenith angle at all seasons has been found at LF.[31] The transition from night to day propagation has been studied by Belrose,[32] who found that a sudden decrease of field strength occurs just before ground sunrise at the path mid-point, when the solar zenith angle reaches 98° (this angle corresponds to sunrise at a height of about 60 km).

Fig. 5(b) shows measurements made in Japan[33] of a 1850 kHz pulse transmission; this frequency is outside the MF broadcasting band but similar results would be expected at the high-frequency end of the band. Measurement of a pulse transmission enabled the sky-wave to be distinguished from the ground wave, which provided a convenient reference level. Unlike LF, the field strength is least at mid-day because ionospheric absorption is greatest at this time of day; even lower mid-day field strengths would be expected at the peak of the solar cycle.

The diurnal variation illustrated in Fig. 5 is, of course, governed by the diurnal variation of the ionosphere. During the day, when the critical frequency of the E layer always exceeds 2 MHz, waves at the higher frequencies in

the MF broadcasting band are returned to ground by refraction in the E layer but are greatly attenuated as they pass through the lowest part of the ionosphere (the D region). At LF, however, sky waves undergo partial reflection at the steep electron-density gradient at the base of the ionosphere and do not penetrate into the D region to any great extent. After sunset the D region decays rapidly and waves in both bands propagate with reduced attenuation. As the critical frequency of the E layer decreases from about 1·5 MHz at sunset to 0·5 MHz late at night, waves at the upper frequencies in the MF band eventually penetrate the E layer and are then reflected by the F layer, which has a much higher critical frequency.* After sunrise the critical frequency of the E layer increases rapidly and waves in the MF band often propagate efficiently via the E layer for up to an hour, before being attenuated by the increased ionization in the D region.

Although sky waves are always weaker during the day than at night, they may still be strong enough to cause interference, especially at LF during the winter months.[34] Because of the large seasonal variation, further discussion of daytime propagation is deferred until Section 4.

The variation which takes place during the night is easier to describe if it is related to the times of sunset and sunrise. As single-hop propagation predominates over paths shorter than 2000 km, sunset and sunrise times for the path mid-point are used as references for these paths. On longer paths the transitions between day and night propagation are controlled at the ionospheric reflection point where the sun sets last or rises first; for convenience this point is assumed to be 750 km from one end of the path. Also for convenience, the times at which the upper limb of the sun sets or rises when seen from sea level are used because these are readily obtained from published tables.[35] Although the sun sets about 40 minutes later in the E layer its rays are considerably weakened by their passage through the Earth's atmosphere and there is therefore some justification for adopting ground sunset and sunrise times as references.

Diurnal variations expressed in terms of sunset and sunrise times are shown in Figs. 6 to 8. In every case, the field strength has been normalised to that observed five or six hours after sunset.

A great deal of information about diurnal variation has been obtained from an analysis of EBU and OIRT measurements[36] which has been carried out by the BBC with the aid of a computer.** The EBU/OIRT data consist of median field strengths for half-hour periods from 1430 to 0530 GMT. In the BBC analysis, each field strength was converted to the value corresponding to minimum solar activity by applying the solar-activity correction given in the footnote on page 109 of Reference 1, using the actual sunspot number observed earlier that day. Field strengths for half-hour time blocks before and after sunset were then derived by linear interpolation between adjacent measured values. After this process had been repeated for a series of days, median, quasi-maximum and quasi-minimum field strengths were determined for each time block. Several options were possible in selecting the series of days. They could, for example, be all the days on which measurements were made during a whole year, or they could be chosen from a specified month over a period of several years.

As the EBU measurements ended at 0530 GMT, the variation at sunrise was observed only during the summer months. Consequently, analysis of EBU data

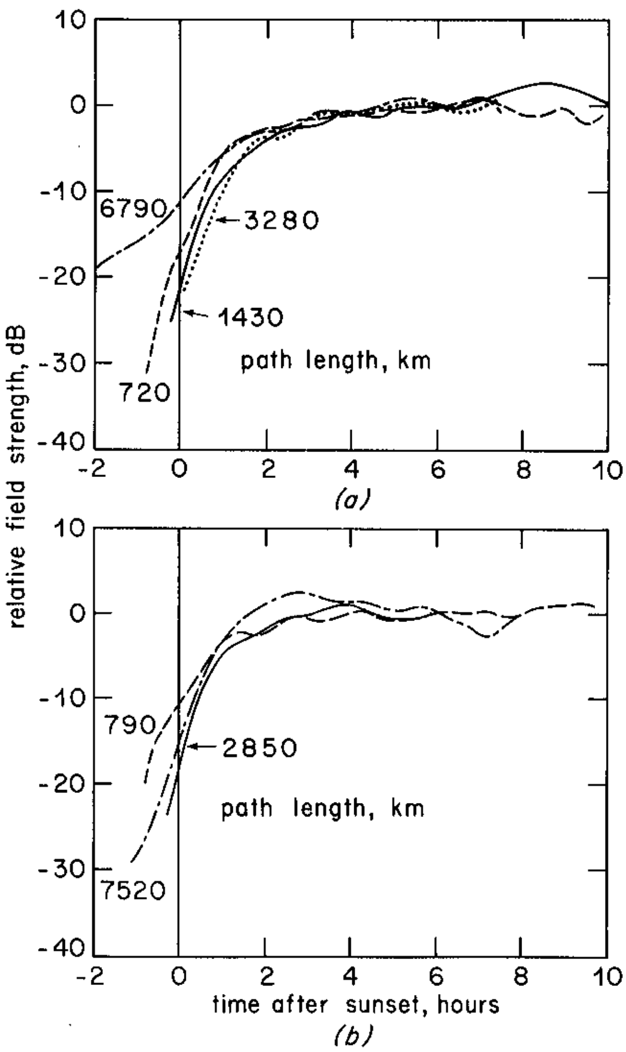

Fig. 6 - Diurnal variation; effect of path length

(a) 845 kHz
(b) 1466 and 1602 kHz

* In the measurements shown in Fig. 5(b), the large scatter in the monthly median values for December which occurs after midnight probably arose because waves penetrated the E layer on some nights but not on others. The much smaller scatter of the June measurements is thought to be due to the persistence throughout the night of propagation via the sporadic-E layer.[33]

** The computer program was written by Dr. J.O. Drewery.

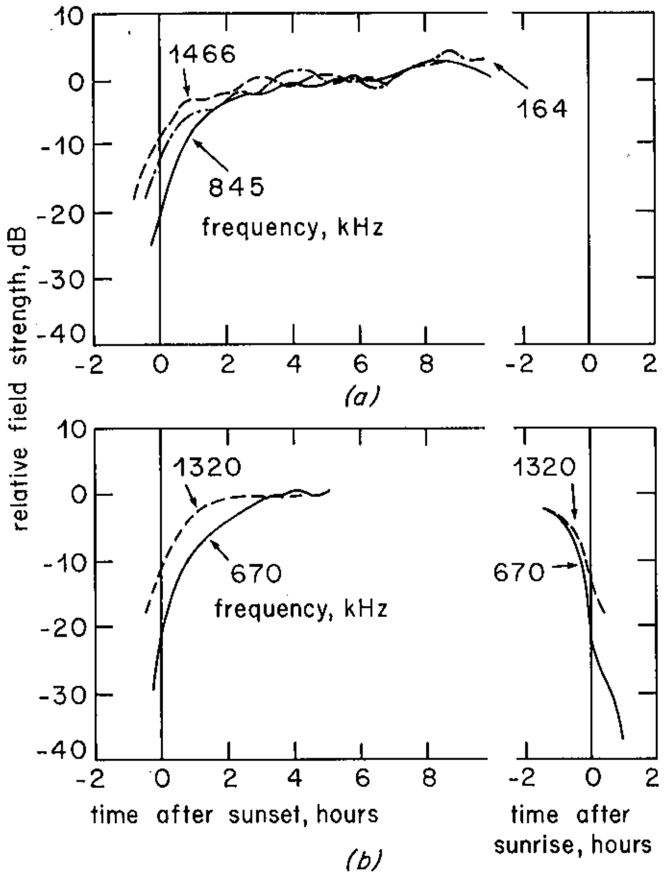

Fig. 7 - Diurnal variation: effect of frequency

(a) European paths
(b) Indian paths (Reference 38)

for complete years gives no information about the average variation at sunrise.

Fig. 6 shows the influence of path length on diurnal variation. Fig. 6(a) shows measurements of Rome (845 kHz) made over the whole year at Chatonnaye (720 km), Tatsfield (1430 km) and in the Azores (3280 km) while measurements of Monte Carlo (1466 kHz) made at Jurbise (790 km) and the Azores (2850 km) are compared in Fig. 6(b). Also included in Fig. 6 are the results of measurements of Rome (845 kHz) and Munich (1602 kHz) made at Tsumeb, S.W. Africa during June 1971.[21] Although the measurements at Tsumeb were subsequently extended to a whole year, the published results[37] are not referred to sunset and sunrise times.

Fig. 6 shows a slight tendency for the onset of night-time propagation to be progressively delayed as the path length increases, probably because of the greater day-time ionospheric absorption on longer paths. The anomalous result observed on the Rome-Tsumeb path (6790 km), shown in Fig. 6(a), may have been caused by interference from a co-channel transmitter at Pietermaritzburg, South Africa, which would be received at Tsumeb in June at least two hours before the Rome transmission.*

Fig. 7 shows how diurnal variation on long single-hop paths (1100 to 1700 km) depends on frequency. Fig. 7(a) is derived from EBU measurements made over complete years on the following paths: Allouis — Enkoping (164 kHz, 1690 km), Rome — Tatsfield (845 kHz, 1430 km) and Monte Carlo — Wittsmoor (1466 kHz, 1100 km). Fig. 7(b) compares measurements made on two frequencies for more than a year, over a 1310 km path in India.[38] A tendency for the onset of night-time propagation to be delayed at the lower frequencies in the MF band is shown by both the European and Indian measurements; this may be due to greater day-time absorption at the lower frequencies. At LF, however, the rise at sunset is similar to that observed at the higher frequencies in the MF band, probably because daytime LF waves do not penetrate so deeply into the absorbing region of the ionosphere. The Indian measurements show that the transition at sunrise is faster than at sunset,

* In June the sun sets at the mid-point of the Pietermaritzburg — Tsumeb path some 2½ hours before it sets at the northern end of the Rome — Tsumeb path.

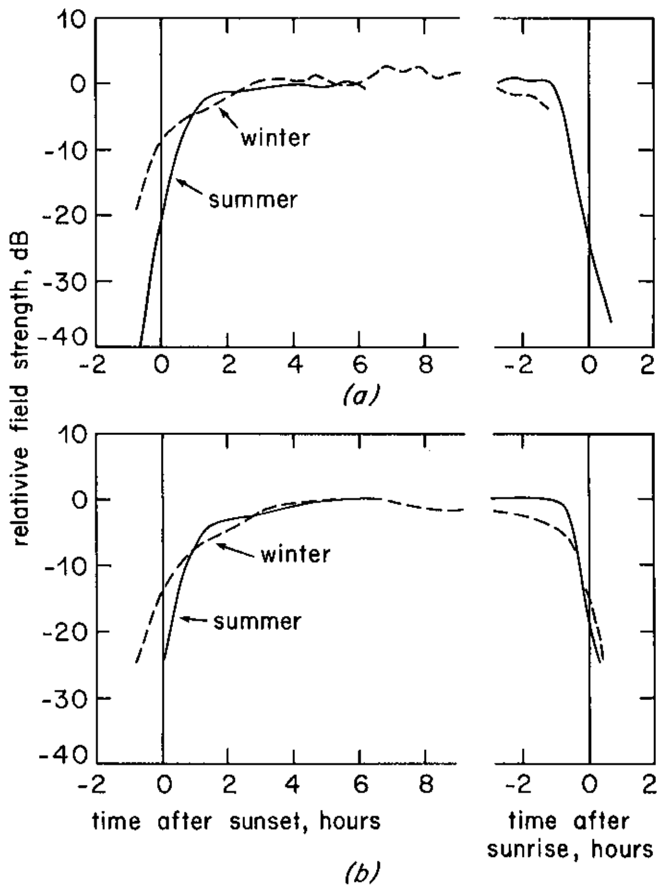

Fig. 8 - Diurnal variation: seasonal effect

(a) European path
(b) Australian paths (Reference 39)

and that the field strength decreases more rapidly at the lower frequency, again because of greater day-time absorption

Fig. 8 shows the difference in diurnal variation between summer and winter which occurs in temperate latitudes. Since the curves are normalised to the field strength 6 hours after sunset, they do not show the seasonal variation of the night-time field strength, discussed in the next section. Diurnal variations for two months at mid-winter and two months at mid-summer, derived from the EBU measurements made for 5 years over the Rome-Belgrade path (845 kHz, 740 km), are shown in Fig. 8(a). Similar results have been obtained in India.[38] Fig. 8(b) shows averaged Australian measurements for June (winter) and December (summer) for a 700 km path and for frequencies in the range 900 to 1100 kHz, derived from Fig. 5 of Reference 39. The similarity between the two sets of curves suggests that there is very little difference in diurnal variation between the northern and southern hemispheres.

The CCIR has adopted an average diurnal variation curve, shown in Fig. 8 of Reference 2, which is consistent with all the measurements illustrated in Figs. 6 to 8. Recent BBC measurements, however, have shown that field strengths sometimes decrease at sunrise less rapidly than the CCIR curve indicates, especially in winter. The variation at sunrise therefore needs to be studied further.

4. Seasonal variation

Although the median field strength measured late at night varies to some extent during the year, the overall variation seldom exceeds 10 dB. Sky-wave signals observed during the day, however, vary to a much greater extent. As the daytime and night-time seasonal variation are unrelated and are quite different in character, they are considered separately.

4.1. Seasonal variation at night

Fig. 8 of CCIR Report 264-3 (Reference 1) is a contour plot which illustrates the combined effect of seasonal and diurnal variation at MF during the night. Fig. 5 of CCIR Report 431-1 (Reference 39) is a similar plot for Australia. The most noticeable features of these two plots are the maxima which occur in spring and autumn and the minimum which occurs in the summer months, when the nights are too short for nocturnal conditions to become fully established.

To be consistent with Section 3, the seasonal variation of the field strength 6 hours after sunset should ideally be studied. Most published measurements, however, describe seasonal variations at a fixed time, usually midnight. As the two contour plots referred to above show that there is very little difference between seasonal variations observed either at midnight or at 6 hours after sunset, no distinction will be made between seasonal-variation curves drawn for these two alternative reference times which coincide, in any case, at the equinoxes.

Fig. 8 of CCIR Report 264-3 is based on average results derived by the EBU[40] from measurements made in 1959 and 1960 of the Rome transmission (845 kHz), at various distances between 700 and 2200 km. Fig. 9 of CCIR Report 264-3 shows seasonal-variation curves for midnight derived from similar measurements made by the OIRT.[41,42] The OIRT curves for MF are consistent with the EBU contour plot but the OIRT curve for 164 kHz shows the opposite trend, with pronounced maxima at midsummer. EBU measurements at 164 kHz analysed by the BBC also show summer maxima but recent BBC measurements of a higher frequency in the LF band (Tipasa, Algeria, 251 kHz) show very little seasonal variation.

Other measurements on European MF paths have been reported to the EBU by Norddeutscher Rundfunk.[43] Seasonal variations on longer paths have been measured for the EBU in Finland[44] and for the ABU in India.[45] Field strengths measured on the Batra – Helsinki path (620 kHz, 3260 km) and on the Riyadh – Helsinki path (5875 kHz, 4290 km) showed pronounced spring and autumn maxima, the overall variation during the year being 15 dB in both cases. The Batra transmission showed a similar variation when measured at New Delhi (path length 4380 km).

At near-vertical incidence, field strengths observed from 2 to 7 hours after sunset at 827 kHz in Europe were about 9 dB stronger in summer than in winter.[46] This difference may arise because F-layer reflections predominate in winter but reflection from the sporadic-E layer is more likely to occur in summer; the change in path length alone would account for about 6 dB of the difference.

There appears to be very little published information about seasonal variation in America although the large spread in median field strengths observed during the course of a year on many paths in the USA[47] suggests that the variation may be greater than in Europe. This view is supported by other American measurements,[48] made at 770 kHz over a 1300 km path.

Seasonal variations in Australia[49] are similar to those observed in Europe, the smallest field strengths occurring in summer in both regions. Although diurnal and seasonal variations observed in Australia and Europe have been compared,[50] there does not appear to be any simple way to describe seasonal variation because it depends on too many factors; these include path length, frequency, geographic latitude and possibly geographic location. The results of all known measurements have therefore been summarised in Table 1, which shows how seasonal maxima and minima differ from the annual median field strength for midnight. Table 1 does not include measurements made over some Indian paths[38] or over long trans-equatorial paths[37] because neither set of measurements shows any obvious seasonal trend.*

* The overall variation of monthly median field strengths was less than 5 dB on the Indian paths and was about 10 dB on the trans-equatorial paths.

TABLE 1

Seasonal variation of night-time field strength

Frequency kHz	Path length km	Geographic Latitude of Mid-Point	Region Traversed	Field Strength Relative to Annual Median, dB				Overall Variation dB	References
				Spring	Summer	Autumn	Winter		
164	1009	51°N	Europe	−1·9	2·7	−1·8	0	4·6	1 (Fig. 9). 41. 42
280	1800	16°N	India	−3	− 4	0	4	8	27 (Fig. 3)
587	4290	42°N	Asia, Europe	6	− 9	5	0	15	44
620	3260	46°N	Asia, Europe	3	−12	2	0	15	
620	4380	30°N	Asia	4	− 7	5	0	12	45 (Corrigendum 1)
760	3130	31°N	Asia	3	− 6	3	2	9	
770	1300	42°N	N. America	5	−10	1	4	15	48
827	38	43°N	Europe	—	5	—	−4	9	46
845	700-2200	37°-48°N	Europe	1·5	−3·5	3·5	−1·5	7	1 (Fig. 8), 40
845	1143	50°N	Europe	1·0	−2·0	1·0	−0·3	3	1 (Fig. 9), 41, 42
900-1100	700	36°S	Australia	1	− 1	1·5	−1	2·5	39 (Fig. 5)
1160	610	51°N	Europe	0	− 3	3	0	6	43
1345	2830	29°N	Asia	2	− 3	2	−1	5	45 (Corrigendum 1)
1466	1057	51°N	Europe	1·4	−1·6	1·4	−0·8	3	1 (Fig. 9), 41, 42
1538	405	52°N	Europe	1	0	−2	2	4	43
1602	1575	54°N	Europe	1·5	1	−1·5	0	3	44

Table 1 shows that the overall variation at MF tends to decrease with increasing frequency. The tendency for maxima to occur in spring and autumn is observed on all oblique-incidence MF paths but one maximum only is observed at near-vertical incidence. At LF the seasonal variation has the opposite trend to that normally observed at MF. Similar conclusions have been derived from measurements made in the USSR.[28]

4.2. Seasonal variation during the day

In Europe, daytime sky-wave field strengths are much greater in winter than in summer; at LF the winter daytime field strength may be only 10 dB below the night-time value. Fig. 9 shows typical monthly median midday field strengths for LF and MF measured at Helsinki,[51] expressed in dBs relative to the annual median night-time value for 6 hours after sunset. The curves are asymmetrical and the rapid increase which occurs in the autumn is sometimes referred to as the "November effect". The variation at LF is similar to that observed at 191 kHz on a 1173 km path between Sweden and the UK by Belrose[32,52] but it has a smaller amplitude. Much smaller variations have been measured at LF in India,[31] where the difference between summer and winter mid-day field strengths was found to be less than 6 dB on the 1650 km Tashkent – Delhi path; throughout the year the daytime field strength was about 25 dB below the night-time value and 10 dB stronger than the estimated ground wave.*

Fig. 9 also shows MF sky-wave field strengths measured at noon in Japan,[53] expressed in dBs relative to the annual median field strength for midnight. The seasonal variation is much smaller than in Northern Europe. Ionospheric absorption measurements[54] made at noon at 1550 kHz over a 530 km path in Southern India showed a different trend, however, the field strength being lowest at the equinoxes and about 10 dB greater in July and December.

* Private communication from Dr. Mangal Sain.

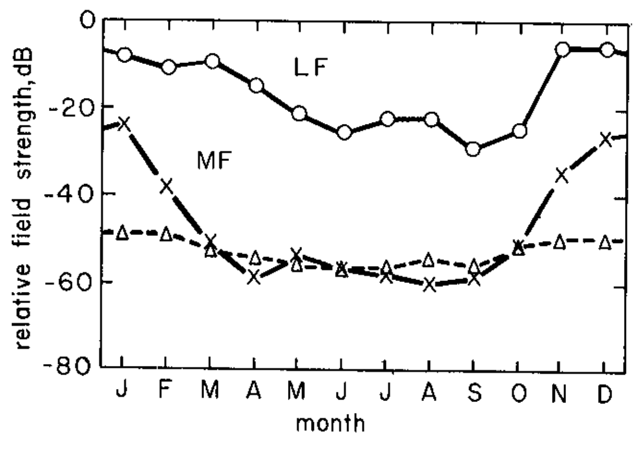

Fig. 9 - Seasonal variation of daytime field strength

——— European measurements
– – – Japanese measurements
O Allouis (France) – Helsinki, 164 kHz, 2067 km
X Cluj (Romania) – Helsinki, 1151 kHz, 1492 km
Δ Sapporo (Japan) – Hiraiso (Japan), 750 kHz, 740 km

Reference 51 contains daytime measurements of more than 200 LF and MF transmissions, made near mid-day from one to four times per month over a 4-year period. Although the measurements do not distinguish between ground waves and sky waves, the type of propagation can usually be determined. Measurements made over 21 paths which were sufficiently long for the ground wave to be unimportant, but short enough for sky-wave signals to be measured during the summer, have been studied by the BBC.[55] Fig. 10 shows median field strengths (relative to night-time values) measured in December on these paths, together with the range of values encountered during the 4 years. The daytime field strength decreases within and above the LF broadcasting band but is almost independent of both frequency and distance within the MF band. Although the comparatively high field strengths observed in December at Helsinki may be partly due to the short winter day at high latitudes, most of the ionospheric reflection points were no further north than the United Kingdom.

5. Solar-cycle variation

The variation in sky-wave field strength which takes place during a solar cycle is difficult to study because observations must be continued for several years. Care must also be taken to distinguish solar-cycle variations from seasonal and other short-period variations. Consequently information about solar-cycle variation is rather sparse.

5.1. Solar-cycle variation at night

All the available evidence shows that MF sky-wave field strengths are greatest at solar cycle minimum and decrease as the sunspot number increases, by an amount which seems to depend mainly on geographical location. In Europe the relationship between field strength and sunspot number was first studied by the EBU,[13] who concluded that solar activity reduces field strengths by $0{\cdot}02R$ dB, where R is the sunspot number, regardless of the distance between transmitter and receiver. On theoretical grounds, however, the field-strength reduction would be expected to be roughly proportional to the path length. This was confirmed by a re-analysis of the EBU data by the BBC,[56] who found that field strengths measured shortly before midnight decreased by $Rd \times 10^{-5}$ dB, where d is the great-circle distance in km. Except at very short distances this reduction is approximately equal to $Rp \times 10^{-5}$ dB, where p is the oblique path length via the ionosphere, and this alternative formula has been adopted by the CCIR[2] for use at MF in Europe. The OIRT have measured field-strength reductions which are twice as large at 845 kHz but which appear to be insignificant at 1466 kHz.[41,42]

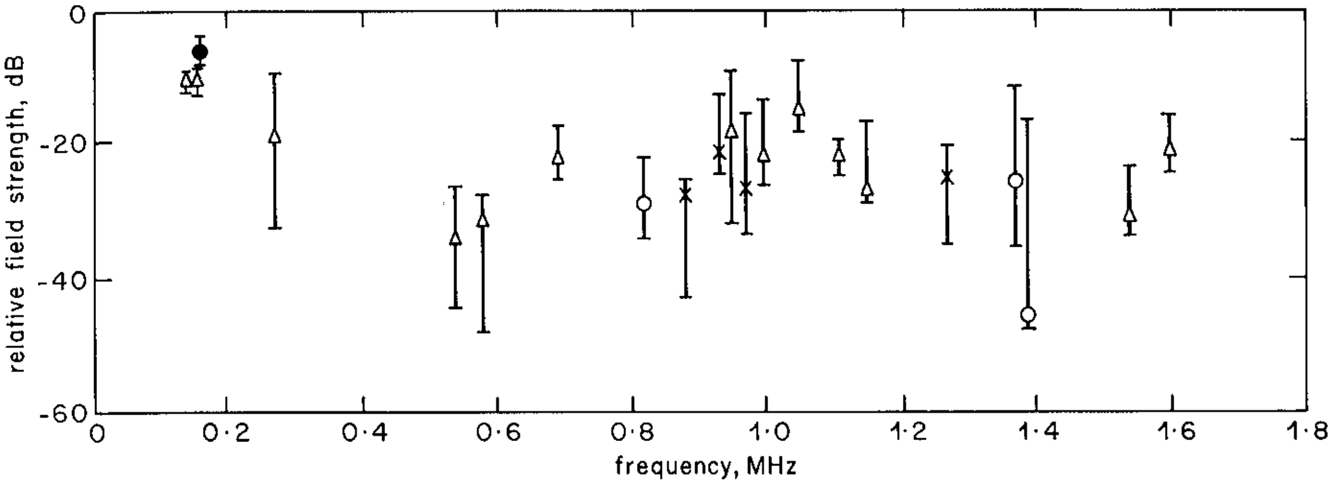

Fig. 10 - Daytime field strengths measured at Helsinki in December

Path length

O Less than 1000 km
X About 1100 km
Δ About 1400 km
● 2067 km

Points show median values for the 4 years and lines indicate the spread of values

The reduction due to solar activity is much greater in North America than in Europe. For example, median field strengths measured near midnight on two paths of about 600 km were found to decrease by more than 6 dB at the peak of the solar cycle;[57] this reduction is more than four times greater than that observed in Europe at the same time of night. In Figs. 1 and 2 of Reference 57 the measured field strengths are compared not only with the Zurich sunspot number but also with the magnetic index,* and it can be seen that, although the field strength depends mainly on sunspot number, it is also influenced by magnetic activity. A 7 dB variation was observed between 1936 and 1940 on a 1300 km North American path by Stetson,[48] who found that field strength showed better correlation with the area occupied by sunspots within ±15° of the sun's equator than with the Wolf sunspot number R. Between 1945 and 1947 an even greater variation (15 dB) was observed on the same path although the range of sunspot numbers was almost the same as in the 1936-1940 period.[58] These observations suggest that the Wolf sunspot number R may not be the most suitable index to describe long-term field-strength variations.

The most comprehensive information about long-term field strength in North America is contained in Reference 47, which gives the results of measurements made by the FCC on 26 paths of various lengths, in some cases for periods as long as 20 years. The basic data are the field strengths exceeded, for various percentages of nights during individual years, by median field strengths for one-hour periods centred on 2 hours after sunset. The results for any given percentage are therefore free of diurnal and seasonal effects. A regression analysis similar to that described in Reference 56 has been carried out by the BBC on these data, annual sunspot numbers and field strengths exceeded for 50% of nights being taken as independent and dependent variables respectively. In Fig. 11 the regression coefficients calculated for each path are plotted against the slant path length p. A

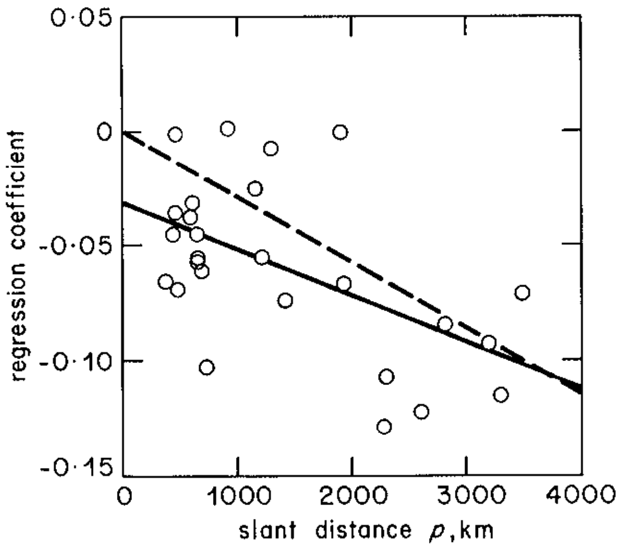

Fig. 11 - Variation of regression coefficient with distance in North America

Regression line
"Least squares" line through origin

* For a discussion and definition of magnetic index, see Section 1.4.2. of Physics of the Earth's upper atmosphere, edited by C.O. Hines et al, published by Prentice-Hall 1965.

further regression analysis, with p as the independent variable and the regression coefficient as the dependent variable, gave the regression line shown in Fig. 11; unlike the corresponding regression line of Reference 56, it does not pass through the origin. Also shown in Fig. 11 is a "least squares" line passing through the origin; this has a gradient which is almost three times greater than that of the European regression line and corresponds to a field-strength reduction approximately equal to $3Rp \times 10^{-5}$ dB. A factor of 4, rather than 3, has been provisionally adopted by the CCIR for North America.[2]

An independent analysis of the same basic data has yielded a solar-activity correction which depends on frequency and geomagnetic latitude as well as sunspot number and path length. Although the evidence suggests that the field-strength reduction becomes greater as the geomagnetic latitude increases, there is insufficient difference in geomagnetic latitude between Europe and North America to explain why field-strength variations in North America are so much greater.

In Australia, quasi-maximum field strengths measured over three paths of lengths between 630 and 1320 km were found to decrease by 5 dB for sunspot numbers up to about 80, but no particular correlation was found for higher sunspot numbers.[49,60] To compare the variation in Australia with that in Europe, MF field strengths measured during one-hour periods extending from 1½ to 2½ hours after sunset, on three Australian paths, were analysed by the BBC by the method described in Reference 56. The measurements were made at weekly intervals over a 5-year period which covered the extremes of the solar cycle. On two of the paths the solar-activity reductions were found to be significantly greater than those given by the European formula $Rp \times 10^{-5}$ dB but on the third path the measured variation was similar to that in Europe. Although this result suggests that the effect of solar activity may be greater in Australia than in Europe, it is perhaps worth noting that the solar activity regression coefficients for several European paths were significantly greater than those calculated from the European formula. Consequently there is not sufficient justification at present for adopting a different formula for Australia.

In tropical regions, there is unlikely to be any appreciable field-strength reduction with increasing solar activity because ionospheric absorption is relatively small.

At LF, measurements made by the OIRT[41,42] on a 1009 km path showed median field strengths decreasing by about 4 dB as the sunspot number increases by about 100; this variation is four times greater than given by the expression $Rd \times 10^{-5}$ which applies in Europe at MF. An analysis by the BBC[61] of measurements made by the EBU and OIRT over 11 European paths of various lengths showed field strengths decreasing with increasing solar activity (as at MF) for paths shorter than 2000 km but having the opposite trend on longer paths. As the evidence was rather inconclusive, corrections for solar activity are not at present applied to LF propagation by the CCIR.[2]

5.2. Solar cycle variation during the day

There is very little information about the effect of solar activity on daytime propagation. Measurements made in India[54] at 1550 kHz show field strengths decreasing with increasing solar activity, as at HF, because of greater ionospheric absorption. At LF, however, increased solar activity also reduces the reflection height. Consequently daytime LF field strengths could be either lower or higher at sunspot maximum, depending on whether absorption or reflection height is the most important factor. Although Fig. 10 of CCIR Report 265-3 (Reference 30) suggests that the higher daytime field strengths are likely to occur at sunspot maximum, this prediction should be treated with caution because it is based almost entirely on vertical-incidence VLF measurements.

6. Conclusions

The conclusions derived from this study may be summarised as follows:

Sky-wave signals vary continually in strength, an effect known as fading. The fading rate, defined as the number of times the median field strength is exceeded in a given time, is proportional to frequency and also depends on the angle of incidence at the ionosphere. On long-distance paths, E-layer reflections predominate and the fading rate for a frequency of 1 MHz is about 10 per hour in Europe; fading rates about three times greater have been measured in Japan. This comparatively slow fading is replaced by more rapid fading if F-layer reflections occur or if two propagation modes of comparable strength are received simultaneously.

At the higher frequencies in the MF band, the field strength observed during two or three fading cycles usually obeys the Rayleigh distribution. With this distribution, the median field strength is exceeded by at least 5·2 dB for 10% of the fading period and falls at least 8·2 dB below the median for a further 10% of the time. At LF the difference between the quasi-maximum and the median is somewhat less (typically 3 dB at night and 1·7 dB during the day) and the distribution more closely resembles the log-normal.

Median field strengths measured at a given time vary randomly from night to night, with a log-normal distribution. The spread of values, measured over a period of days which is short enough to exclude seasonal and solar-cycle effects, shows no obvious dependence on frequency or path length. On most paths the difference between the field strengths exceeded on 10% and 50% of the nights lies between 3·5 and 8·8 dB; a difference of 5·5 dB may be regarded as typical. LF sky waves propagating during the winter daytime vary from day to day in a similar manner.

Both the short-period and day-to-day variations contribute to the overall variation of the received signal. In planning broadcasting services it is reasonable to assume

that the field strength exceeded for 10% of the total time on a series of nights, during short periods centred on a specific time, is

5 dB greater at LF, during the day
6·5 dB greater at LF, at night
8 dB greater at MF, at night

than the median field strength derived from propagation curves or formulae.

LF and MF sky-wave field strengths increase at sunset and decrease at sunrise. At any given frequency the rates of increase and decrease are almost independent of path length, although there is a slight tendency for the onset of night-time propagation to be progressively delayed as the path length increases. There is also a tendency for the onset of night-time propagation to be delayed at the lower frequencies in the MF band, but not in the LF band. In temperate latitudes the transition from day to night conditions starts in winter at least an hour before sunset but in summer the transition starts nearer to sunset and takes place more rapidly. The average diurnal-variation curve contained in CCIR Report 575 is consistent with all the measurements described here, but recent evidence suggests that it may be in error at sunrise and that further measurements should be made at this time. At LF the rapid decrease at sunrise is often followed by a gradual rise to a mid-day maximum which may be only 10 dB weaker than the night-time field strength.

LF and MF sky waves are also subject to seasonal variations. At night, MF sky waves propagating in temperate latitudes are strongest in spring and autumn and are weakest in summer and winter, the summer minimum being the more pronounced. The overall variation may be as much as 15 dB at the lowest frequencies in the MF band, decreasing to about 3 dB at upper end of band. At LF the seasonal variation at night has the opposite trend, with a pronounced summer maximum. The seasonal variation is much smaller in tropical latitudes.

Large seasonal variations are observed in daytime in Europe, where LF sky waves propagating in winter are at least 20 dB stronger than in summer and may be only 10 dB below night-time values. At MF the seasonal variation in Europe exceeds 30 dB but the winter daytime field strength is at least 10 dB lower than at LF. Smaller seasonal variations occur nearer the equator, where the daytime sky-wave field strength throughout the year is comparable with that observed in Europe during the summer months.

Solar activity reduces MF night-time sky-wave field strengths, by an amount which is proportional to path length and which also depends on geographic location. The reduction is three or four times greater in North America than in Europe or Australia but in tropical latitudes it is believed to be negligible. Solar activity has little or no effect on LF propagation at night and it is uncertain whether it has any influence on LF daytime propagation. Although the Wolf sunspot number is used at present, some observations suggest that this may not be the best index to describe long-term field-strength variations.

7. Acknowledgement

Thanks are due to Mr. J.P. Crean for developing the computer program described in Section 3 and for the subsequent analysis of EBU data which he carried out.

8. References

1. Sky-wave propagation curves between 300 km and 3500 km at frequencies between 150 kHz and 1600 kHz in the European broadcasting area. CCIR Report 264-3, Geneva 1974.

2. Methods for predicting sky-wave field strengths at frequencies between 150 kHz and 1600 kHz. CCIR Report 575, Geneva 1974.

3. The accuracy of predictions of sky-wave field strength in Bands 5 (LF) and 6 (MF). CCIR Report 432, Geneva 1974.

4. Fading of radio signals received via the ionosphere. CCIR Report 266-3, Geneva 1974.

5. McNICHOL, R.W.E. 1949. The fading of radio waves of medium and high frequencies. Proc. Instn. elect. Engrs., 1949, **96**, Part III, pp. 517-524.

6. KING, J.W. 1957. The fading of radio waves reflected at oblique incidence. J. atmos. terr. Phys., 1958, **12**, pp. 26-33.

7. SULANKE, H. *and* TÄUMER, F. 1967. Die Eigenschaften von Häufigkeitsverteilungen der Raumwellenfeldstärke im Frequenzbereich zwischen 150. . . . 1600 kHz. Tech. Mitt. RFZ 1967/4, pp. 192-195; 1968/1, pp. 32-37.

8. Properties of sky-wave field strength distribution in Bands 5 and 6 (LF and MF) (150 to 1600 kHz) CCIR Doc. VI/195, 19 June 1969. (OIRT).

9. NAKAGAMI, M. 1943. Statistical character of short-wave fading. J. Inst. elect. Commun. Engrs. Japan 1943, **27**, pp. 145-150.

10. RICE, S.O. 1944. Mathematical analysis of random noise. Bell Syst. tech. J., 1944, **23**, pp. 282-332, 1945, **24**, pp. 46-156.

11. VENKATESWARLU, P. *and* SATYANARAYANA, R. 1958. Fading of radio waves, Curr. Sci., 1958, No. 8, p. 296.

12. Preliminary investigations into indirect-ray propagation of medium waves and quality of reception in the secondary service area. CCIR Doc. X/14, 18 April 1962

(India).

13. EBERT, W., EHLERS, H. *and* DOBIASCH, R. 1959. Ionospheric propagation on long and medium waves. EBU Rev. Part A, 1959, No. 57. pp. 2-16.

14. SAWAMURA, E. 1953. Study on fading of broadcasting waves (540–1600 kc). NHK Technical Research Laboratory Report. Tokyo, Japan, February 1953.

15. Interim report on medium frequency sky-wave measurements. Australian Broadcasting Control Board Technical Report No. 13, March 1955.

16. HARWOOD, J. 1953. Spaced-receiver experiments on radio waves of 19 km wavelength. Proc. Instn. elect. Engrs., 1954, **101**, Part IV, 7, pp. 183-186.

17. BELROSE, J.S. 1968. Low and very low frequency radio wave propagation. AGARD Lecture Series XXIX, Leicester, 1968, pp. IV-1 to IV-115. (See Fig. IV-67).

18. GRISDALE, G.L., MORRIS, J.G. *and* PALMER, D.S. 1956. Fading of long-distance radio signals and a comparison of space and polarisation diversity in the 6-18 Mc/s range. Proc. Instn. elect. Engrs., 1957, **104**, Part B, 13, pp. 39-51.

19. GROSSKOPF, J. 1953, Statistische Untersuchungen an Kurzwellenübertragungswegen, Fernmeldetech. Z., 1953, **8**, pp. 373-378.

20. Medium frequency sky-wave field strength predictions for Australia. CCIR Doc. VI/205, 23 June 1966 (Australia).

21. Sky-wave propagation at frequencies between approximately 150 and 1500 kHz. CCIR Doc. 6/86, 24 March 1972 (Federal Republic of Germany).

22. BARGHAUSEN, A.F. 1965. Medium-frequency sky-wave propagation in middle and low latitudes. IEEE Trans. Broadcast. 1966, BC-12, pp. 1-14.

23. LAUTER, E.A. et al. 1965. Space and time variations of long wave ionospheric absorption at small solar heights and at night. Geomag. and Aeron. (English translation) 1965, V, pp. 813-821.

24. DELLINGER, J.H. *and* COSENTINO, A.T. 1940. A radio transmission anomaly; co-operative observations between the United States and Argentina. Proc. Inst. Radio Engrs., 1940, **28**, pp. 431-437.

25. Medium wave ionospheric propagation in Africa. CCIR Doc. VI/75, 31 May 1965 (EBU-OIRT-URTNA).

26. DIEMINGER, W. *and* ELLING, W. 1975. On the reflection of medium wavelength during night over distances 0–500 km. Nachrtech. Z., 1975, **28**, pp. 364-367.

27. SEN, A.K. *and* SAHA, B. 1974. Regular behaviour of the field strength of LF radio signals measured in Calcutta. J. Instn. Electron. and Telecommun. Engrs., New Delhi, 1975, **21**, pp. 584-8.

28. VILENSKIY, I.M., UDAL'TSOV, A.N. *and* SHLYUGER, I.S. 1968. Field strength of radio waves in the 150–1500 kHz range that propagate to great distances from the transmitter. Geomagn. and Aeron., 1970, **10**, pp. 204-207,

29. STARICK, E. *and* TAUMER, F. 1968. Die Ausbreitung der Langwellen am Tage über die D-Region der Ionosphäre. Tech. Mitt. RFZ, 1968/2, pp. 89-96; 1968/3, pp. 143-144.

30. Sky-wave propagation at frequencies below 150 kHz with particular emphasis on ionospheric effects. CCIR Report 265-3, Geneva 1974.

31. MANGAL SAIN, RAO, M.K. *and* KUMAR, Y. 1968. Some studies of longwave propagation of Radio Tashkent 164 kHz. J. Instn. Telecommun. Engrs., New Delhi, 1968, **14**, pp. 533-536.

32. BELROSE, J.S. 1956. Some investigations of the lowest ionosphere. Ph.D. Thesis, University of Cambridge, first copy 1956, revised copy 1957.

33. WAKAI, N. et al. 1969. Observations of the ionospheric absorption at oblique incidence during the ISQY. J. Radio Res. Labs, Japan, 1969, **16**, pp. 1-16.

34. BELL, C.P. *and* KNIGHT, P. 1976. Daytime sky-wave propagation in the LF broadcasting band. EBU Doc. Com.T.(B)217, CCIR IWP 6/4 Doc. 26, 1st Sept. 1976 (UK).

35. Brown's Nautical Almanac, Glasgow, Brown, Son and Ferguson Ltd. published annually.

36. EBERT, W. 1962. Ionospheric propagation on long and medium waves. EBU Doc. TECH 3081, March 1962.

37. EYFRIG, R., HOMUTH, H. *and* VOGT, K. 1974. LF and MF field strength measurements over great distances – final report. Nachrtech. Z., 1975, **28**, pp. 30-32.

38. RAO, C.S.R., SUNDARAM, T.R. *and* ROY, J.M. 1973. Ionospheric propagation of medium frequencies. Indian J. Radio and Space Phys. 1974, **3**, pp. 142-145.

39. Analysis of sky-wave propagation measurements for the frequency range 150 kHz to 1600 kHz. CCIR Report 431-1, Geneva 1974.

40. Variations du champ nocturne au cours de l'année. EBU Doc. Com.T(B)57, 14 November 1962.

41. TÄUMER, F. *and* STARICK, E. 1969. Jahreszeitliche Feldstärkevariationen im Lang- und Mittel-

wellenbereich, Tech. Mitt. RFZ, 1/1969, pp. 16-19.

42. Seasonal variations of field strength in bands 5 and 6 (LF and MF). CCIR Doc. VI/197, 17 June 1969 (OIRT).

43. Atténuation de l'onde d'espace diurne. EBU Doc. Com.T(B)83, 7 March 1966.

44. Evaluation of MF field strength recordings made at Helsinki 1966-1973. EBU Doc. Com.T(B)177, 8 October 1973.

45. Long-distance night-time sky-wave propagation curves in Band 6(MF), CCIR Doc. 6/289, 30 January 1974, with Corrigendum 1 (Japan).

46. Field strength of the sky-wave on frequency 827 kc/s at quasivertical incidence in medium latitudes. CCIR Doc. VI/208, 24 June 1966 (Bulgaria).

47. Long term sky-wave field strength measurements in the 550-1600 kHz frequency band. FCC Report No. R-7103, Washington USA, 10 May 1971.

48. STETSON, H.T. 1941. Diurnal and seasonal variations in radio reception at broadcast frequencies during the last sunspot cycle. Massachusetts Institute of Technology reports and papers on terrestrial magnetism and electricity, 1941, pp. 457-459.

49. Medium frequency sky-wave characteristics. CCIR Doc. VI/88, 4 April 1962 (Australia).

50. Medium frequency sky-wave field strength predictions, CCIR Doc. 6/177, 5 February 1973 (Australia).

51. Daytime LW/MW field-strength measurements. EBU Doc. Com.T(B)213, 1 April 1976.

52. BELROSE, J.S. et al. 1958. The engineering of communication systems for low radio frequencies. Proc. Inst. Radio Engrs., 1959, **47**, pp. 661-680.

53. Field strength of the sky-waves at frequency 750 kHz in Japan. CCIR Doc. 6/273, 16 November 1973 (Japan).

54. SATYANARAYANA SARMA, M., GOPAL RAO, M.S.V. *and* ANJANEYULU, C. 1970. Ionospheric absorption measurements at 1·55 MHz by the URSI A_3 method, Indian J. pure & appl. Phys., 1970, **8**, pp. 523-25.

55. Daytime LF and MF field-strength measurements at Helsinki. EBU Doc. Com.T(B)220.

56. DREWERY, J.O. *and* KNIGHT, P. 1971. Variation of medium-frequency sky-wave field strength with solar activity in Europe. BBC Research Department Report 1971/11.

57. BARGHAUSEN, A.F. *and* LILLE, D.A. 1965. Some evidence of the influence of long-term magnetic activity on medium frequency sky-wave propagation. Proc. IEEE, 1965, **53**, pp. 2115-6.

58. STETSON, H.T. 1948. Changes in ionization and radio reception during the sunspot period 1944-1947. Terr. Magn. atmos. Elect., **53**, pp. 449-454, 1948.

59. WANG, J.C.H. 1976. Medium-frequency sky-wave propagation in North America. CCIR IWP 6/4 Doc. 27, 16 Sept. 1976 (USA).

60. DIXON, J.M. 1959. Some medium frequency sky-wave measurements. Proc. IRE Australia, 1960, **21**, pp. 407-409.

61. KNIGHT, P. *and* CREAN, J.P. 1972. Variation of low-frequency sky-wave field strength with solar activity in Europe. BBC Research Department Report 1972/12.

HR/JUC